CLAIMS

1. A method for inspection of a sample that includes a first layer having a known reflectance property and a second layer formed over the first layer, the method comprising:

directing radiation toward a surface of the sample;

sensing the radiation reflected from the surface so as to generate a reflectance signal as a function of elevation angle relative to the surface;

identifying a feature in the reflectance signal due to reflection of the radiation from the first layer;

calibrating the reflectance signal responsively to the identified feature and to the known reflectance property of the first layer; and

analyzing the calibrated reflectance signal to determine a characteristic of the second layer.

2. The method according to claim 1, wherein the radiation comprises X-rays.

3. The method according to claim 1, wherein sensing the radiation comprises receiving the radiation at an array of detector elements having an array axis perpendicular to the surface.

4. The method according to claim 3, wherein receiving the radiation comprises:

translating the array between at least first and second positions along a direction parallel to the array axis;

generating first and second reflectance signals due to the radiation received by the detector elements in the first and second positions; and

combining the first and second reflectance signals so as to generate an enhanced reflectance signal.

5. The method according to claim 1, wherein identifying the feature comprises finding a location of a shoulder in the reflectance signal corresponding to a critical angle for total external reflection from the first layer.

6. The method according to claim 5, wherein calibrating the reflectance signal comprises comparing the location of the shoulder to a known value of the critical angle, which is determined by a known density of the first layer.

7. The method according to claim 6, wherein calibrating the reflectance signal comprises finding a zero angle in an angular scale of the reflectance signal based on the location of the shoulder and the known value of the critical angle.

8. The method according to claim 5, wherein the critical angle for total external reflection from the first layer is a first critical angle, and wherein analyzing the calibrated reflectance signal comprises determining a calibrated value of a second critical angle for total external reflection from the second layer.

9. The method according to claim 8, wherein the first and second layers have respective first and second densities, and wherein analyzing the calibrated reflectance signal comprises estimating the second density based on the calibrated value of the second critical angle.

10. The method according to claim 9, wherein the second density is substantially less than the first density.

11. The method according to claim 10, wherein the first layer comprises silicon, and wherein the second layer comprises a porous dielectric material.

12. Apparatus for inspection of a sample that includes a first layer having a known reflectance property and a second layer formed over the first layer, the apparatus comprising:

a radiation source, which is adapted to direct X-rays toward a surface of the sample;

a detector assembly, which is arranged to sense the radiation reflected from the surface so as to generate a reflectance signal as a function of elevation angle relative to the surface; and

a signal processor, which is coupled to receive and process the reflectance signal by identifying a feature in the reflectance signal due to reflection of the radiation from the first layer and calibrating the reflectance signal responsively to the identified feature and to the known reflectance property of the first layer, and to analyze the calibrated reflectance signal to determine a characteristic of the second layer.

13. The apparatus according to claim 12, wherein the radiation comprises X-rays.

14. The apparatus according to claim 12, wherein the detector assembly comprises an array of detector elements having an array axis perpendicular to the surface.

15. The apparatus according to claim 14, wherein the detector assembly comprises a motion element, which is adapted to translate the array between at least first and second positions along a direction parallel to the array axis, so that the array generates first and second

reflectance signals due to the radiation received by the detector elements in the first and second positions, and

wherein the signal processor is adapted to combine the first and second reflectance signals in order to generate an enhanced reflectance signal.

16. The apparatus according to claim 12, wherein the feature identified by the signal processor comprises a shoulder in the reflectance signal corresponding to a critical angle for total external reflection from the first layer.

17. The apparatus according to claim 16, wherein the signal processor is adapted to calibrate the reflectance signal by comparing a location of the shoulder in the reflectance signal to a known value of the critical angle, which is determined by a known density of the first layer.

18. The apparatus according to claim 17, wherein the signal processor is adapted to find a zero angle in an angular scale of the reflectance signal based on the location of the shoulder and the known value of the critical angle.

19. The apparatus according to claim 16, wherein the critical angle for total external reflection from the first layer is a first critical angle, and wherein the signal processor is adapted to determine a calibrated value of a second critical angle for total external reflection from the second layer by analyzing the calibrated reflectance signal.

20. The apparatus according to claim 19, wherein the first and second layers have respective first and second

densities, and wherein the signal processor is adapted to estimate the second density based on the calibrated value of the second critical angle.

21. The apparatus according to claim 20, wherein the second density is substantially less than the first density.

22. The apparatus according to claim 21, wherein the first layer comprises silicon, and wherein the second layer comprises a porous dielectric material.

23. Apparatus for inspection of a sample, comprising:

a radiation source, which is adapted to direct X-rays toward a surface of the sample;

a detector assembly, which comprises:

an array of detector elements, which are arranged along an array axis substantially perpendicular to the surface and are mutually separated by a predetermined pitch, and which are operative to receive the X-rays reflected from the surface and to generate signals responsively to the received radiation; and

a motion element, which is coupled to shift the array of detector elements in a direction parallel to the array axis between at least first and second positions, which positions are separated one from another by an increment that is not an integer multiple of the pitch; and

a signal processor, which is coupled to combine the signals generated by the detector assembly in at least the first and second positions so as to determine an X-ray reflectance of the surface as a function of elevation angle relative to the surface.

24. The apparatus according to claim 23, wherein the signal processor is adapted to interleave the signals generated by the detector assembly in at least the first and second positions in order to determine the X-ray reflectance of the surface.

25. The apparatus according to claim 23, wherein the increment is less than or equal to one half of the pitch.

26. The apparatus according to claim 23, wherein the array comprises a linear array, and wherein the detector elements have a transverse dimension, perpendicular to the array axis, that is substantially greater than a pitch of the array.

27. The apparatus according to claim 23, wherein the array comprises a two-dimensional matrix of the detector elements, and wherein the detector assembly is adapted to bin the detector elements in respective rows of the array along a direction perpendicular to the array axis.

28. A method for inspection of a sample, comprising:

directing X-rays toward a surface of the sample;

configuring an array of detector elements, which are mutually separated by a predetermined pitch, to receive the X-rays reflected from the surface while resolving the received radiation along an array axis substantially perpendicular to the surface;

shifting the array of detector elements in a direction parallel to the array axis between at least first and second positions, which positions are separated one from another by an increment that is not an integer multiple of the pitch;

receiving at least first and second signals generated by the detector elements responsively to the X-

rays received thereby in at least the first and second positions, respectively; and

combining at least the first and second signals so as to determine an X-ray reflectance of the surface as a function of elevation angle relative to the surface.

29. The method according to claim 28, wherein combining at least the first and second signals comprises interleaving the signals.

30. The method according to claim 28, wherein the increment is less than or equal to one half of the pitch.

31. A cluster tool for producing microelectronic devices, comprising:

a deposition station, which is adapted to deposit a thin-film layer over an underlying layer on a surface of a semiconductor wafer, the underlying layer having a known reflectance property; and

an inspection station, comprising:

a radiation source, which is adapted to direct X-rays toward the surface of the wafer;

a detector assembly, which is arranged to sense the radiation reflected from the surface so as to generate a reflectance signal as a function of elevation angle relative to the surface; and

a signal processor, which is coupled to receive and process the reflectance signal by identifying a feature in the reflectance signal due to reflection of the radiation from the underlying layer and calibrating the reflectance signal responsively to the identified feature and to the known reflectance property of the underlying layer, and to analyze the calibrated reflectance signal to determine a

characteristic of the thin-film layer deposited by the deposition station.

32. Apparatus for producing microelectronic devices, comprising:

a production chamber, which is adapted to receive a semiconductor wafer;

a deposition device, which is adapted to deposit a thin-film layer over an underlying layer on a surface of the semiconductor wafer within the chamber, the underlying layer having a known reflectance property;

a radiation source, which is adapted to direct X-rays toward the surface of the semiconductor wafer in the chamber;

a detector assembly, which is arranged to sense the radiation reflected from the surface so as to generate a reflectance signal as a function of elevation angle relative to the surface; and

a signal processor, which is coupled to receive and process the reflectance signal by identifying a feature in the reflectance signal due to reflection of the radiation from the underlying layer and calibrating the reflectance signal responsively to the identified feature and to the known reflectance property of the underlying layer, and to analyze the calibrated reflectance signal to determine a characteristic of the thin-film layer deposited by the deposition device.

33. A cluster tool for producing microelectronic devices, comprising:

a deposition station, which is adapted to deposit a thin-film layer on a surface of a semiconductor wafer; and

an inspection station, comprising:

a radiation source, which is adapted to direct X-rays toward the surface of the wafer;

a detector assembly, which comprises:

an array of detector elements, which are arranged along an array axis substantially perpendicular to the surface and are mutually separated by a predetermined pitch, and which are operative to receive the X-rays reflected from the surface and to generate signals responsively to the received radiation; and

a motion element, which is coupled to shift the array of detector elements in a direction parallel to the array axis between at least first and second positions, which positions are separated one from another by an increment that is not an integer multiple of the pitch; and

a signal processor, which is coupled to combine the signals generated by the detector assembly in at least the first and second positions so as to determine an X-ray reflectance of the thin-film layer as a function of elevation angle relative to the surface.

34. Apparatus for producing microelectronic devices, comprising:

a production chamber, which is adapted to receive a semiconductor wafer;

a deposition device, which is adapted to deposit a thin-film layer on a surface of the semiconductor wafer within the chamber;

a radiation source, which is adapted to direct X-rays toward the surface of the semiconductor wafer in the chamber;

a detector assembly, which comprises:

an array of detector elements, which are arranged along an array axis substantially perpendicular to the surface and are mutually separated by a predetermined pitch, and which are operative to receive the X-rays reflected from the surface and to generate signals responsively to the received radiation; and

a motion element, which is coupled to shift the array of detector elements in a direction parallel to the array axis between at least first and second positions, which positions are separated one from another by an increment that is not an integer multiple of the pitch; and

a signal processor, which is coupled to combine the signals generated by the detector assembly in at least the first and second positions so as to determine an X-ray reflectance of thin-film layer as a function of elevation angle relative to the surface.

35. A method for inspection of a sample, comprising:

directing radiation from a radiation source in a first predetermined position toward a radiation sensor in the second predetermined position;

sensing the radiation that is directly incident on the radiation sensor from the radiation source so as to generate a first direct signal as a function of elevation angle, while a shutter is positioned so as to cut off the radiation at a predetermined cutoff angle;

sensing the radiation that is directly incident on the radiation sensor from the radiation source so as to generate a second direct signal as a function of the elevation angle, while the shutter is positioned so as not to cut off the radiation at the predetermined cutoff angle;

introducing a sample between the radiation source in the first predetermined position and the radiation sensor in the second predetermined position, so that the radiation is incident on a surface of the sample;

sensing the radiation reflected from the surface of the sample onto the radiation sensor so as to generate a first reflectance signal as a function of the elevation angle, while the shutter is positioned so as to cut off the radiation at the predetermined cutoff angle;

sensing the radiation reflected from the surface of the sample onto the radiation sensor so as to generate a second reflectance signal as a function of the elevation angle, while the shutter is positioned so as not to cut off the radiation at the predetermined cutoff angle; and

comparing a first ratio between the first direct signal and the second direct signal with a second ratio between the first reflectance signal and the second reflectance signal in order to find the elevation angle of a tangent to the surface.

36. The method according to claim 35, wherein the radiation comprises X-rays.

37. The method according to claim 35, wherein the radiation sensor comprises an array of detector elements having an array axis perpendicular to the surface of the sample.

38. The method according to claim 37, wherein sensing the radiation to determine the direct and reflectance signals comprises:

translating the array between at least first and second positions along a direction parallel to the array axis;

generating first and second signals due to the radiation received by the detector elements in at least the first and second positions; and

combining at least the first and second signals so as to generate an enhanced signal.

39. The method according to claim 35, and comprising analyzing the first and second reflectance signals so as to determine a property of a thin film layer at the surface of the sample.

40. The method according to claim 35, wherein comparing the first ratio with the second ratio comprises finding a first elevation angle at which the first ratio has a given value and a second elevation angle at which the second ratio has the given value, and determining the elevation angle of the tangent to the surface to be an average of the first and second elevation angles.

41. The method according to claim 40, and comprising taking a difference between the first and second elevation angles so as to determine a minimum elevation angle below which the shutter cuts off the radiation.

42. Apparatus for inspection of a sample, comprising:

a radiation source in a first predetermined position, which is adapted to generate radiation;

a shutter, which is positionable so as to cut off the radiation at a predetermined cutoff angle;

a motion stage, which is configured to position a sample so that the radiation generated by the radiation source is incident on a surface of the sample;

a radiation sensor in a second predetermined position, which is adapted to sense the radiation so as to generate signals responsive to the radiation incident on the radiation sensor as a function of elevation angle, the signals comprising:

a first direct signal responsive to the radiation that is directly incident on the radiation sensor from the radiation source while the shutter is positioned so as to cut off the radiation at the predetermined cutoff angle;

a second direct signal responsive to the radiation that is directly incident on the radiation sensor from the radiation source while the shutter is positioned so as not to cut off the radiation at the predetermined cutoff angle;

a first reflectance signal responsive to the radiation reflected from the surface of the sample onto the radiation sensor while the shutter is positioned so as to cut off the radiation at the predetermined cutoff angle; and

a second reflectance signal responsive to the radiation reflected from the surface of the sample onto the radiation sensor while the shutter is positioned so as not to cut off the radiation at the predetermined cutoff angle; and

a signal processor, which is coupled to compare a first ratio between the first direct signal and the second direct signal with a second ratio between the first reflectance signal and the second reflectance

signal in order to find the elevation angle of a tangent to the surface.

43. The apparatus according to claim 42, wherein the radiation comprises X-rays.

44. The apparatus according to claim 42, wherein the radiation sensor comprises an array of detector elements having an array axis perpendicular to the surface of the sample.

45. The apparatus according to claim 44, wherein the radiation sensor comprises a motion element, which is adapted to translate the array between at least first and second positions along a direction parallel to the array axis, so that the array generates at least first and second signals due to the radiation received by the detector elements in the first and second positions, and

wherein the signal processor is adapted to combine at least the first and second signals in order to generate an enhanced signal.

46. The apparatus according to claim 42, wherein the signal processor is adapted to analyze the first and second reflectance signals so as to determine a property of a thin film layer at the surface of the sample.

47. The apparatus according to claim 42, wherein the signal processor is adapted to find a first elevation angle at which the first ratio has a given value and a second elevation angle at which the second ratio has the given value, and to determine the elevation angle of the tangent to the surface by taking an average of the first and second elevation angles.

48. The apparatus according to claim 47, wherein the signal processor is adapted to take a difference between the first and second elevation angles so as to determine the minimum elevation angle below which the shutter cuts off the radiation.